1
INJURY BIOMECHANICS RESEARCH
Proceedings of the Eighth International Workshop

Rotation Generated Shear Strains in the Brain

by

Carley Ward and Marian Chan
Biodynamics/Engineering, Inc.
P.O. Box 722
Pacific Palisades, CA 90272

INTRODUCTION

Dynamic shear strains and their relationship to brain injury have long been topics of discussion. It has been conjectured that these strains are a primary injury mechanism but it has not been proven, nor have the shears been measured. In this paper, the shear strain injury theory and supporting tests are examined. Shear strains with and without head rotation are computed using a finite element brain model. Patterns of strain are presented and their relationship to injury discussed.

Holbourn's Theory and Tests

Holbourn, in 1943 (1)*, was the first proponent of the shear strain injury theory. It was his opinion that shear strains at any point in the brain are a rough measure of the probability of injury and that these shear strains are produced primarily by angular head acceleration.

Holbourn used a water flask analogy to describe brain strains (1). He states that as the flask rotates, the water tends to lag behind. Water particles attached to the inside surface of the flask become separated from neighboring particles not thus attached, producing large shear strains. Water, he states, being less rigid than brain tissue exaggerates the effect of shearing strains.

He supported his theory with experiments. Planar sections were cut from a gelatin filled skull, placed in a circular polariscope, and subjected to a sudden rotation. High shear strains developed along the outer surface of the gelatin, especially along boney skull discontinuities.

---

* Numbers in parentheses designate references at end of paper.

There was a comparative absence of strains in the section of cerebellum. Holbourn hypothesized that this was due to its small size. Actually, this lack of strain was the result of the planar section. In the tested brain slice, the cerebellum section was completely separated from the cerebrum by a continuous layer of tentorium. No interaction between the cerebellum, brain stem and cerebrum was possible in these planar models since none of the sections included the brain stem.

Displacement Tests

In tests performed at Wayne State University (2) the results were somewhat different. A monkey head was sectioned along the midsagittal plane and encased in plastic so that movement of the brain could be observed. When subjected to translation and rotation, strains developed along the brain-skull interface. But in these tests the largest displacements and strains were in the brain stem with significant strains in the cerebellum. Head rotation produced the greatest response. Because sectioning removed the falx, the support for the tentorium, the partitioning effect of these dural membranes is almost eliminated. The displacement is, therefore, larger than in the living head. Also, the lack of blood pressure increases the response magnitude above the invivo result (3).

ANALYSIS

Finite Element Model

To determine the true strain pattern and relate it to injury, an analytical investigation was performed. A head injury test was simulated using a finite element model of a primate brain, Figure 1. This model and a similar human model have been used extensively in the study of brain stresses (pressures) and contusion injury (3, 4). Here, for the first time, the model is used to compute strain.

In this finite element idealization, three dimensional eight node brick elements represent the soft brain material and contained fluids. Four node membrane elements represent the partitioning folds of dura, the falx and tentorium. The internal shape of the skull is simulated and the opening for the cervical cord included. To simulate the test, the model is mathematically forced to move in space just as the actual skull moves in the event.

Forced Head Motion Test

A head injury test conducted at the University of Pennsylvania (5, 6) was selected for the simulation. The monkey is supine on a hinged table (Figure 2). A movable section of the table under the animal's head is attached to a pneumatic actuator so that thrust of the actuator is converted to rotation of the head. The initial head angle is -26 degrees and the final angle is +35 degrees (measured from the horizontal). A rigid mask attached to the table confines the animal's head, stopping the head at the end of the actuator stroke. A typical head acceleration trace is shown in Figure 3. Acceleration is positive as the head is accelerated in the positive X direction and negative as it is stopped at the end of the stroke.

Simulation Results

To investigate the effects of head rotation, two tests were simulated:

1. the actual test described above, and
2. a hypothetical test equivalent to the actual test with the rotational acceleration removed.

The tangential acceleration at the center of the skull in the first simulation is the translational acceleration used in the second.

Stress Results - A stress gradient develops in the head as the brain tends to lag the skull. Positive stresses (negative pressures) develop in the frontal lobe and negative stresses (positive pressures) develop in the occipital region during the acceleration phase. As the head is stopped the reverse is true. Stresses versus time in a row of midsagittal elements are plotted in Figures 4 and 5. Refer to Figure 6 for element locations. Maximum principal stresses in the frontal lobe, parietal lobe and lower brain stem are listed in Table I. In the high stress regions such as the frontal lobe, the shear stresses are small, the normal stress components being nearly equal. In the lower stress regions like the brain stem, the shear stresses are larger and differences exist between the principal stress components.

A comparison of stresses with and without head rotation shows that head rotation has only a limited effect on the high tensile and compressive stresses, Table I. Differences are generally less than fifteen percent. For a typical comparison of these stresses versus time, refer to Figure 7. The reverse is true for shear stresses; they are significantly affected by head rotation (Table I) as described in the next section on shear strains.

Strain Results - Shear strains predominate. They occur in the cerebrum and the brain stem. Strains develop along curved surfaces of the cerebrum as the brain tends to lag the rotation of the skull. The distribution through the center of the brain is shown in Figures 8 and 9, where strains in a vertical column of elements extending from the cerebrum into the brain stem are plotted. Two rotational patterns evolve, one in the cerebrum and the other in the cerebellum, refer to Figure 10. Strains are highest near the foramen magnum as tissue moves through the opening.

The elimination of rotation has a significant effect on most of the shear strains. Shear strains in the cortex and brain stem near the pons and cerebellar peduncles are reduced, refer to Table II. The difference is shown in Figure 11 where cortex strains with and without rotation are plotted versus time.

DISCUSSION

Shear strains develop along the brain's surface as Holbourn predicted, but shear strains also exist in the cerebellum and brain stem contrary to his theory (1). The pattern of motion he described differs from that computed by the model. Instead of a single swirling motion of the brain, the cerebrum and cerebellum each have their own rotational motion which initiates a complex interaction with the brain stem. The brain stem is further strained by motion through the foramen magnum. Holbourn's use of planar sections and neglect of the brain stem probably contributed to his misconception concerning brain response.

The brain stem response more closely resembles that observed by Hodgson in hemisections of the monkey head (2). These tests confirm the existence of shear strains in the cerebellum and brain stem. The rotational displacements are somewhat different from that predicted by the model because the partitioning effect of the tentorium is nearly eliminated in the sectioning process.

The relationship between head rotation and shear is apparent in both the model and hemisection test; the shear strains are increased by head rotations, Figure 11. Restricting head rotation reduces the strains, but it does not eliminate them as Holbourn conjectured. Some shear strains are caused by head translation.

High normal stresses in the brain are nearly independent of head rotation. These stresses can be calculated reasonably well from just the translational acceleration.

From a research point of view, it is fortunate that the high stress region and high strain region do not coincide. Injuries related to the two types of response can be separated. In the high normal stress regions, contusions occur. In the high shear strain regions, petechia hemorrhages and neuron tears occur. Along the surface of the high strain regions bridging veins rupture and subdural hematomas form.

Because concussion is defined as loss of consciousness, usually associated with a brief period of amnesia, one would expect that the midbrain--the region controlling consciousness and the cortex--the region related to memory should be involved in the concussion-producing response. Since these are the high strain regions, concussion is most likely related to brain shear strains which in turn are affected by head rotation. This finding is supported by animal test results which showed that it was easier to concuss an animal when its head was free to rotate or with rotational head motion (7, 8).

A head injury criterion based on translational acceleration alone, like those now being used, is not adequate for shear strain injuries which depend on head rotation. The brain tolerance level to strain needs to be determined just as the brain's tension and compression stress tolerance levels were determined (3, 4). (Stress magnitudes which produce contusions were determined through finite element simulations of approximately fifty animal and human cadaver head injury tests.)

CONCLUSIONS

Shear strains in the brain have been calculated using a finite element model. The results show the following:

1. A strain pattern develops in the brain which is different from any previously described. High shear strains occur in the brain stem and cerebellum, as well as the cortex and along the cortex surface. Separate rotational displacement patterns exist in the cerebrum and cerebellum due to the partitioning effect of the tentorium.
2. Shear strains are related to head rotation but are not eliminated when head rotation is restricted.
3. Typical injuries in the high strain regions are petechia hemorrhages, tear lesions, vascular rupture, and subdural hematoma. Because the regions of the brain controlling consciousness and memory are subjected to high shear strains, concussion is probably a strain-related injury.

TABLE I

Principal Stresses (PSI)

	El. No.	Translation and Rotation P_1	P_2	P_3	Max. Shear $\frac{P_3-P_1}{2}$	Translation Without Rotation P_1	P_2	P_3	Max. Shear $\frac{P_3-P_1}{2}$
FRONTAL LOBE	4	37.13	37.26	38.83	1.857	36.01	36.06	37.59	0.788
	36	31.15	31.58	33.20	1.025	27.83	28.71	30.34	1.255
	68	25.07	25.33	26.48	.708	21.48	22.63	24.57	1.545
PARIETAL LOBE	16	10.12	12.52	15.43	2.657	14.19	15.25	17.02	1.418
	48	11.22	11.42	12.84	0.811	12.41	12.60	13.78	0.687
	80	8.75	8.91	10.67	0.661	8.52	9.20	9.47	0.472
LOWER BRAIN STEM	144	1.45	4.22	8.84	3.696	1.93	3.99	8.52	3.291
	146	0.15	1.71	6.21	3.030	0.371	2.34	6.32	2.972
	149	0.83	1.26	5.51	2.345	0.72	1.60	4.36	1.821

TABLE II

ELEMENT STRAINS WITH AND WITHOUT HEAD ROTATION –
MAXIMUM z-x SHEAR STRAINS, TEST NO. 8078
(REFER TO FIGURE 6 FOR ELEMENT LOCATIONS)

Element No.	Head Rotation and Translation, Maximum Strain (in./in.)	Head Translation Only Maximum Strain (in./in.)	Difference in Strain Due to Head Rotation	Comments
4	-0.0113	-0.0017	-0.0096	Minimal changes in frontal lobe
8	+0.0179	+0.0267	-0.0088[a]	
12	+0.0470	+0.0355	0.0115	
16	+0.0821	+0.0480	0.0341	Strains decreased significantly in superior cerebrum
20	+0.0933	+0.0519	0.0414	
24	+0.0957	+0.0525	0.0432	
32	+0.0395	+0.0277	0.0118	
36	-0.0303	-0.0253	-0.0050	
52	+0.0482	+0.0413	0.0069	
64	+0.0034	+0.0090	-0.0056[a]	
84	+0.0048	+0.0244	-0.0196[a]	
96	-0.0340	-0.0135	-0.0205	
100	-0.0153	-0.0044	-0.0109	
104	-0.0108	-0.0214	+0.0106[a]	Strain slightly increased in upper brain stem
108	-0.0080	-0.0156	+0.0076[a]	
112	+0.0184	+0.0191	-0.0007[a]	
116	+0.0050	+0.0217	-0.0167[a]	
120	-0.0375	-0.0183	-0.0192	
124	-0.0660	-0.0395	-0.0265	
128	-0.0444	-0.0251	-0.0193	
129	-0.0065	-0.0163	+0.0098[a]	
131	+0.0657	+0.0469	+0.0188	Strains relatively unchanged in upper cerebellum
134	+0.0593	+0.0544	+0.0049	
137	+0.0255	+0.0288	-0.0033[a]	
140	-0.0356	-0.0208	-0.0148	
143	-0.1051	-0.0908	-0.0143	
144	+0.1005	+0.0848	+0.0157	
146	+0.1038	+0.0744	+0.0294	Strains decreased significantly in brain stem near pons
149	+0.0953	+0.0602	+0.0351	
152	+0.0472	+0.0154	+0.0318	
155	+0.0262	+0.0174	+0.0088	
158	-0.2388	-0.2381	-0.0007	Minimal changes in posterior cerebellum and at foramen magnum
163	+0.0699	+0.0713	-0.0014[a]	

[a]Strain is reduced by rotation.

REFERENCES

1. Holbourn, A., Mechanics of Head Injuries, The Lancet, pp. 438-441, October 9, 1943.

2. Hodgson, V. R., and Thomas, L. M., Acceleration Induced Shear Strains in a Monkey Brain Hemisection, Proceedings of 23rd Stapp Car Crash Conference, San Diego, California, 1979.

3. Ward, C., and Chan, M., Finite Element Modeling of the Head and Neck, Chapter in Impact Injury to the Head and Spine, to be published by C. C. Thomas Co., Springfield, Ill.

4. Ward, C., Chan, M., and Nahum, A., Intracranial Pressure - A Brain Injury Criterion, Proceedings of 23rd Stapp Car Crash Conference, Troy, Michigan, 1980.

5. Abel, J. Gennarelli, T. A., and Segawa, H., Incidence and Severity of Cerebral Concussion in the Rhesus Monkey Following Sagittal Plane Angular Acceleration, Proceedings of 22nd Stapp Car Crash Conference, pp. 33-53, 1978.

6. Gennarelli, T. A., Able, J., Adams, H., and Graham, D., Differential Tolerance of Frontal and Temporal Lobes to Contusion Induced by Angular Acceleration, Proceedings of 23rd Stapp Car Crash Conference, pp. 235-255, 1979.

7. Gennarelli, T. A., and Ommaya, A. K., Comparison of Translational Rotational Head Motions in Experimental Cerebral Concussion, Proceedings of 15th Stapp Car Crash Conference, pp. 797-803, 1971.

8. Ommaya, A.K., Rockoff, S. D., and Baldwin, M., Experimental Concussion; A First Report, Journal of Neurosurgery 21-4: 249-265, 1964.

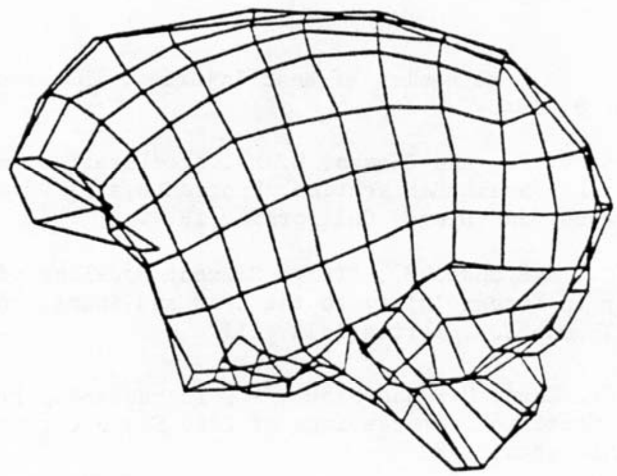

FIGURE 1. Finite element monkey brain model

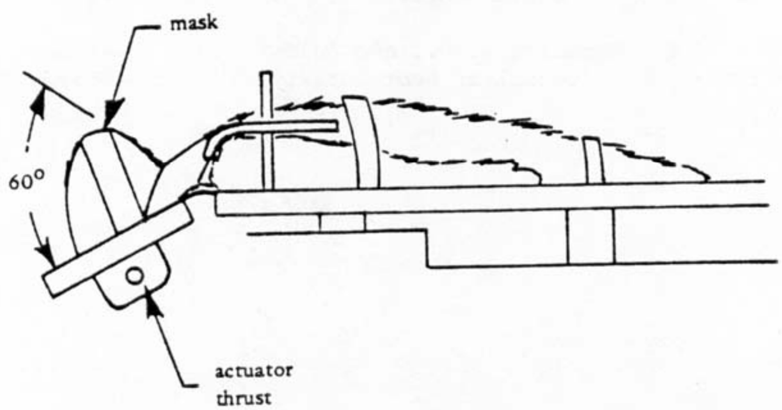

FIGURE 2. Monkey on hinged table. University of Pennsylvania forced head motion tests

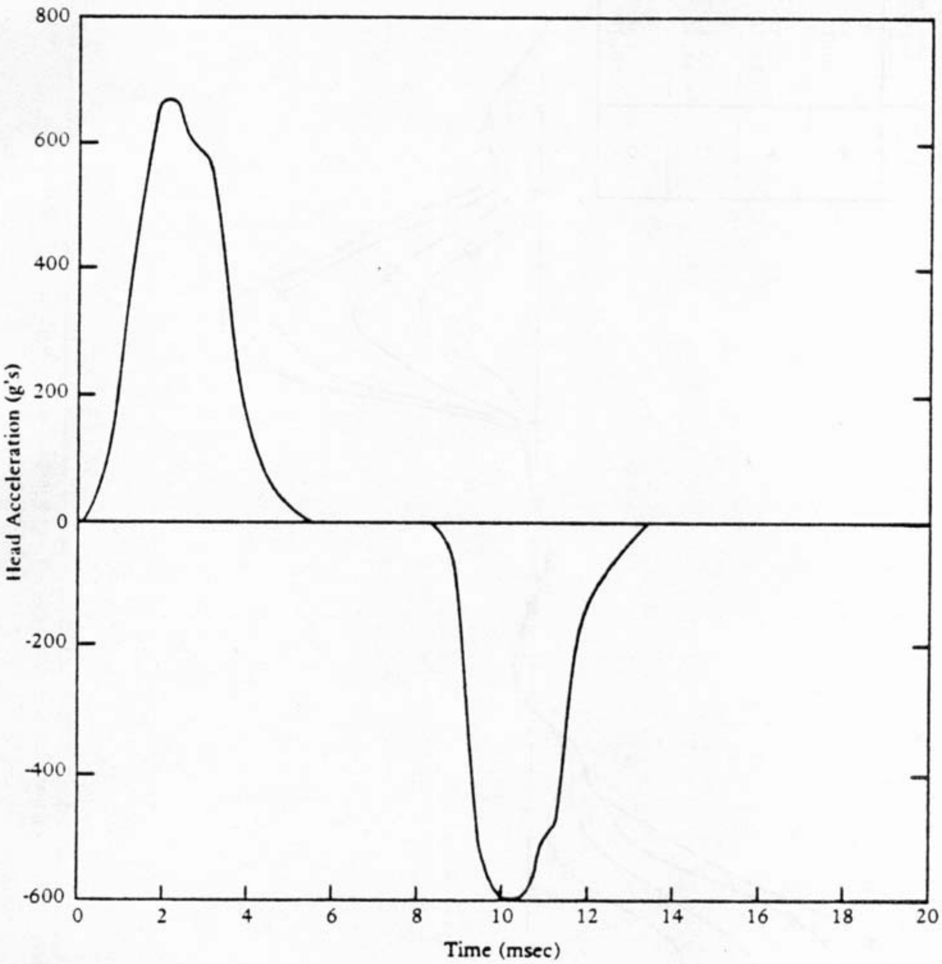

FIGURE 3. Typical tangential head acceleration in University of Pennsylvania forced head motion tests

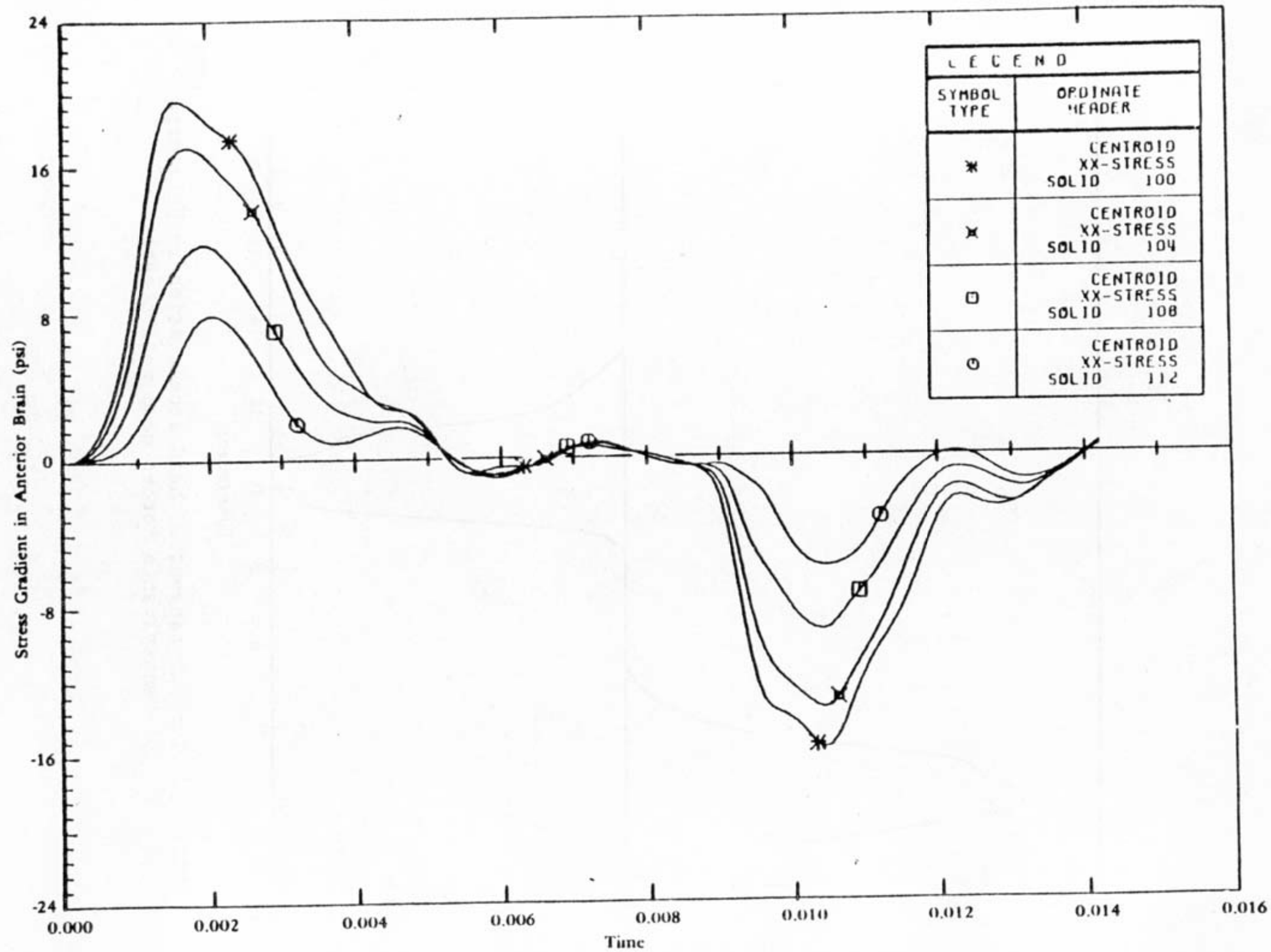

FIGURE 4. Pressure gradient in anterior cerebrum, element stresses versus time in University of Pennsylvania forced head motion test

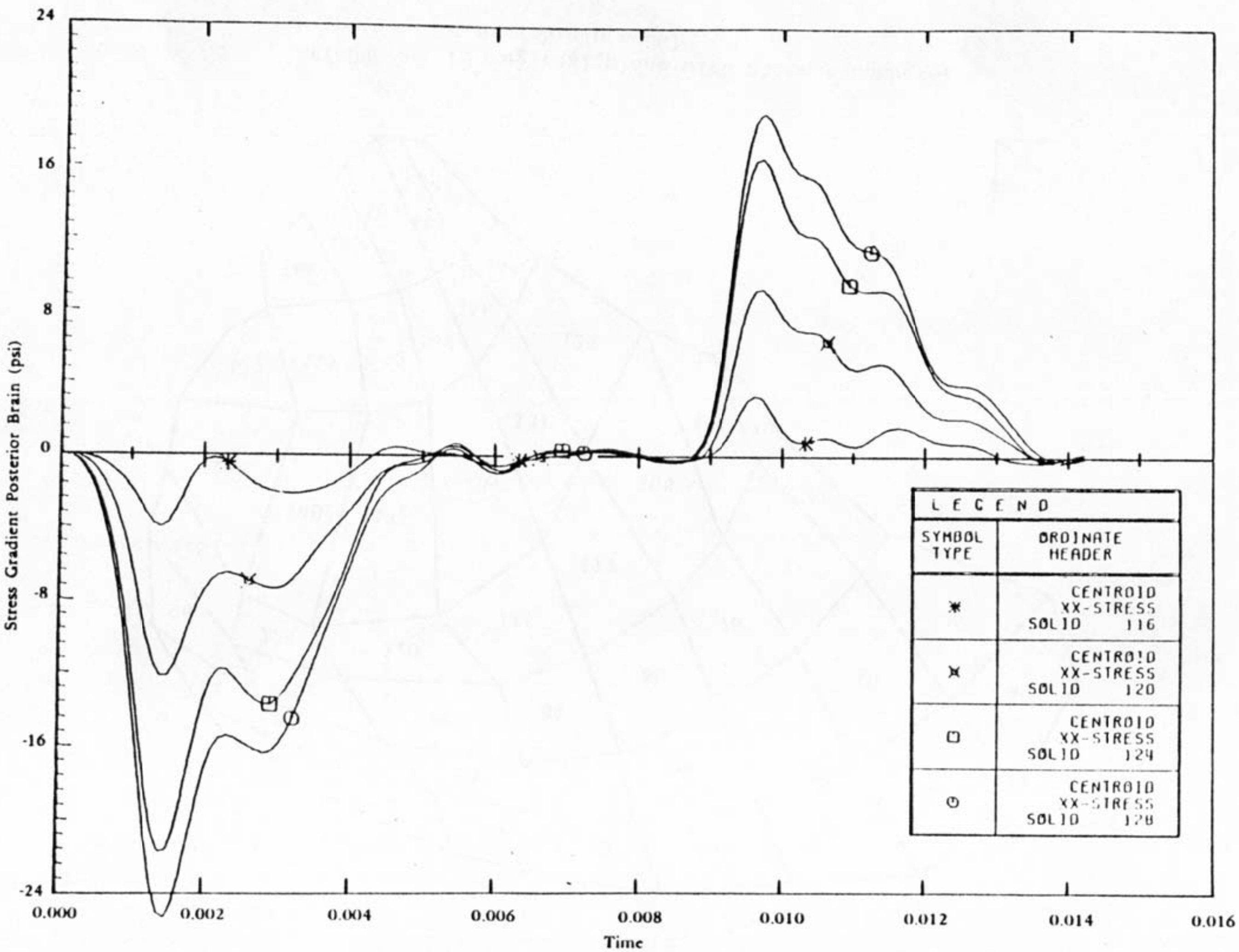

FIGURE 5. Pressure gradient in posterior cerebrum, element stresses versus time in University of Pennsylvania forced head motion test

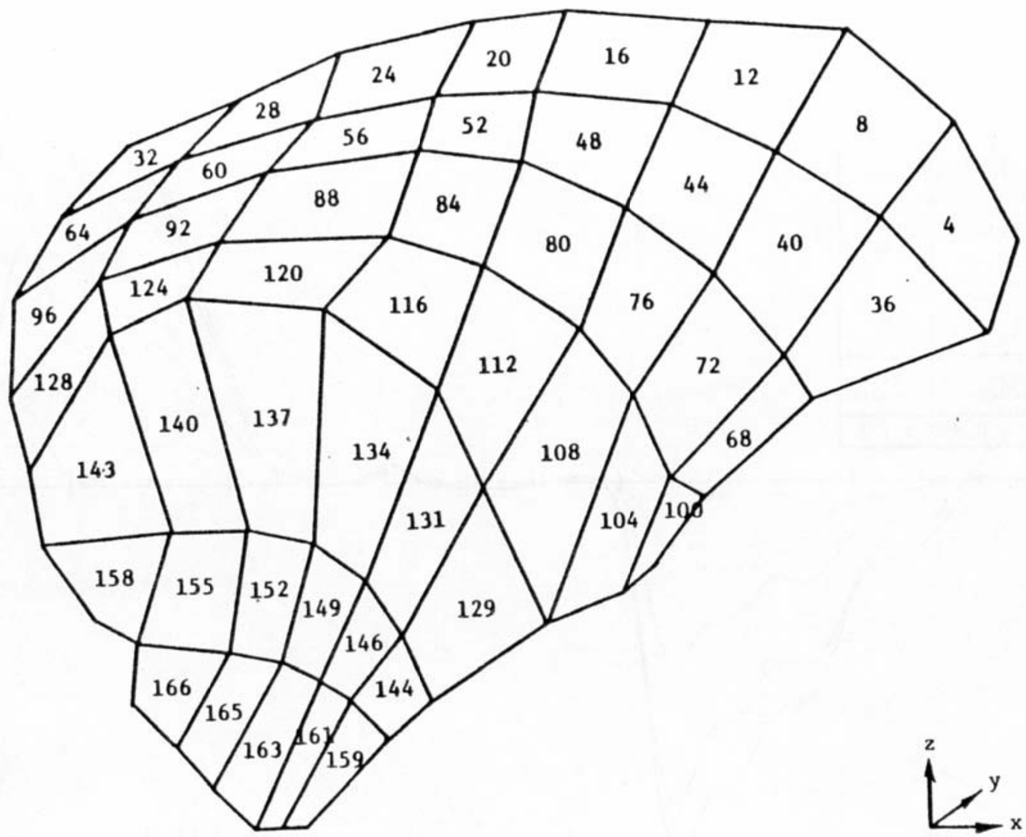

FIGURE 6. Midsagittal plane with element numbers, monkey brain model

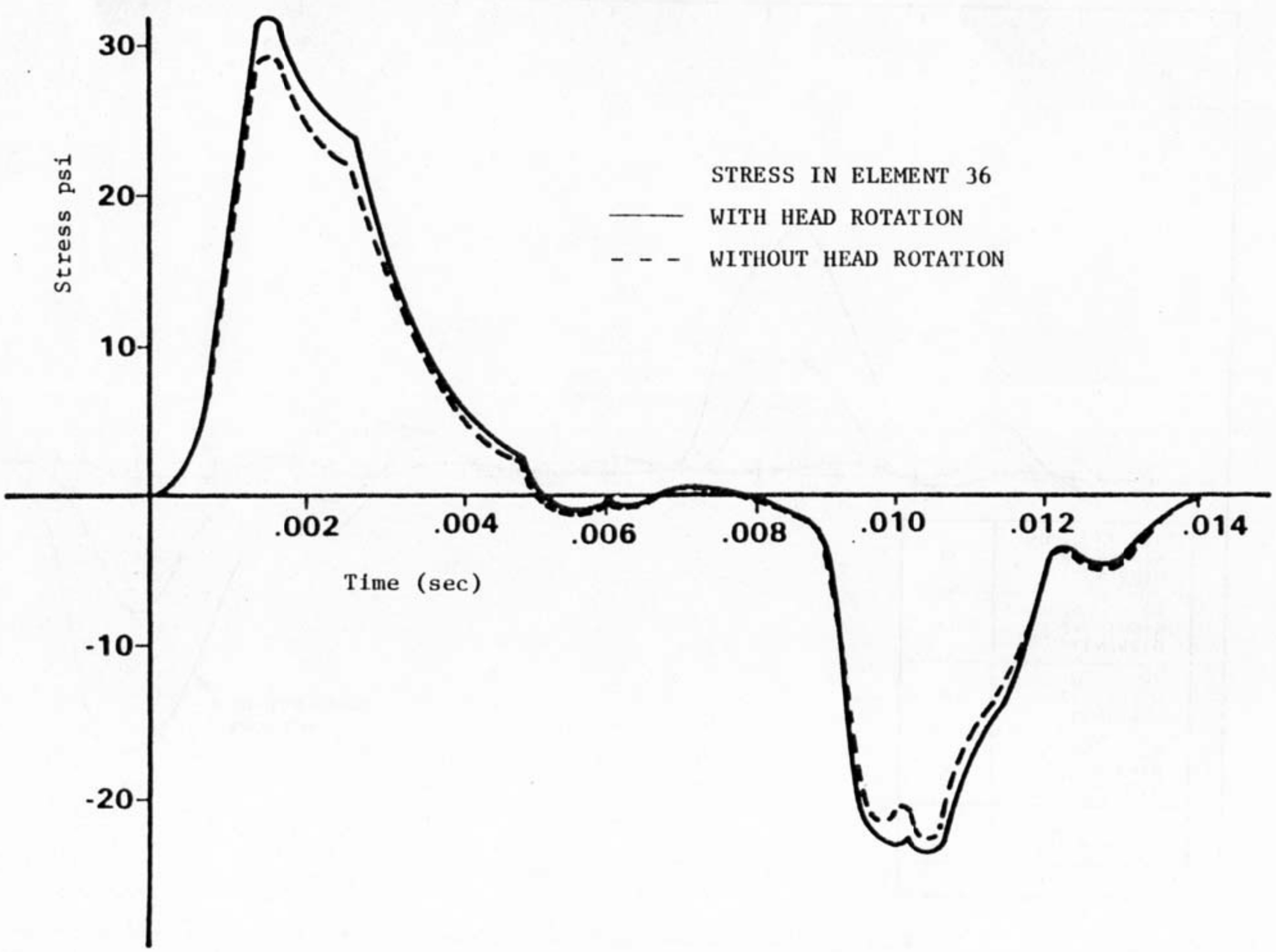

FIGURE 7. Comparison of frontal lobe stress with and without head rotation

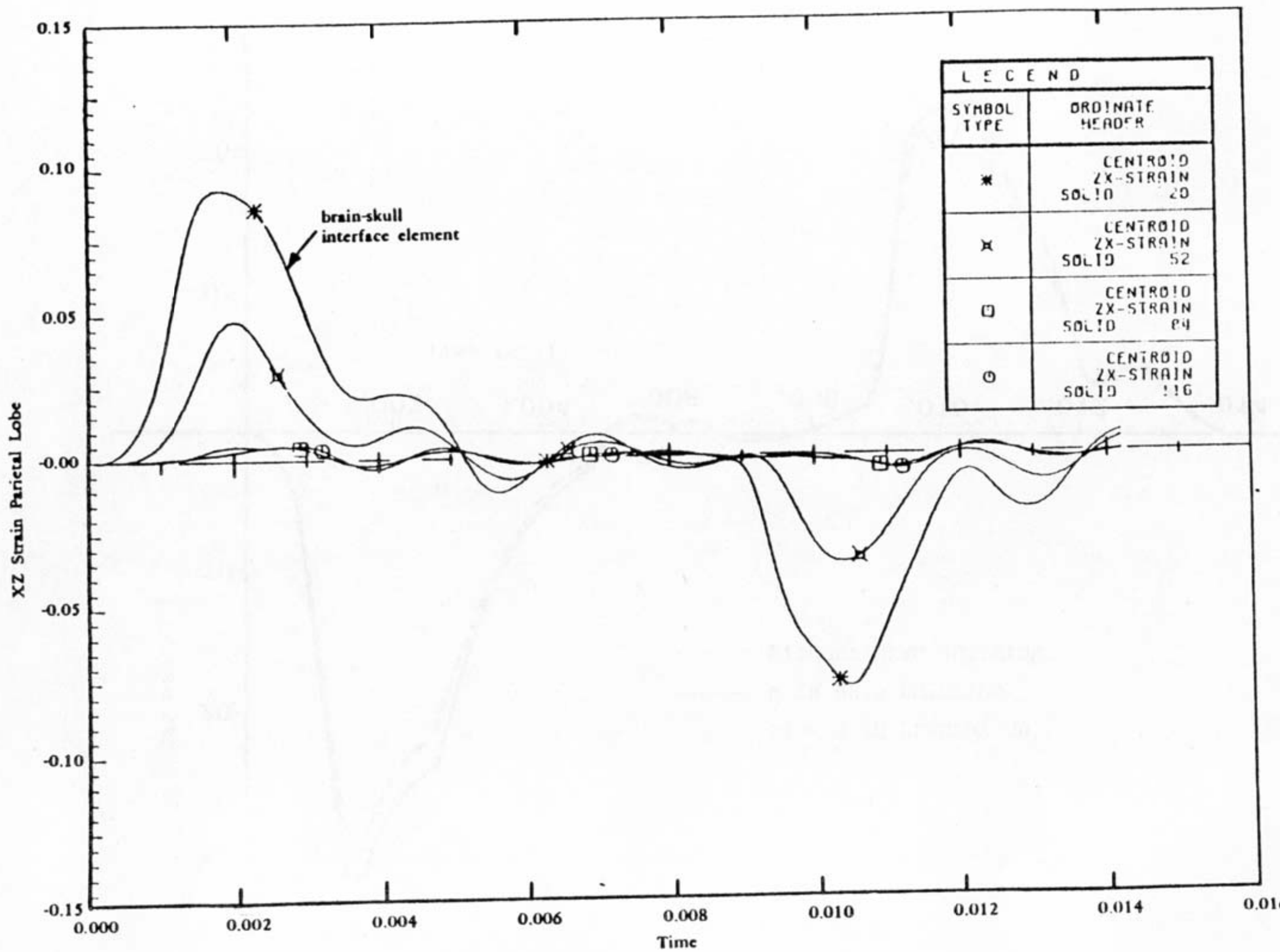

FIGURE 8. X-Z shear strains in vertical column of elements extending from cerebrum to superior brain stem

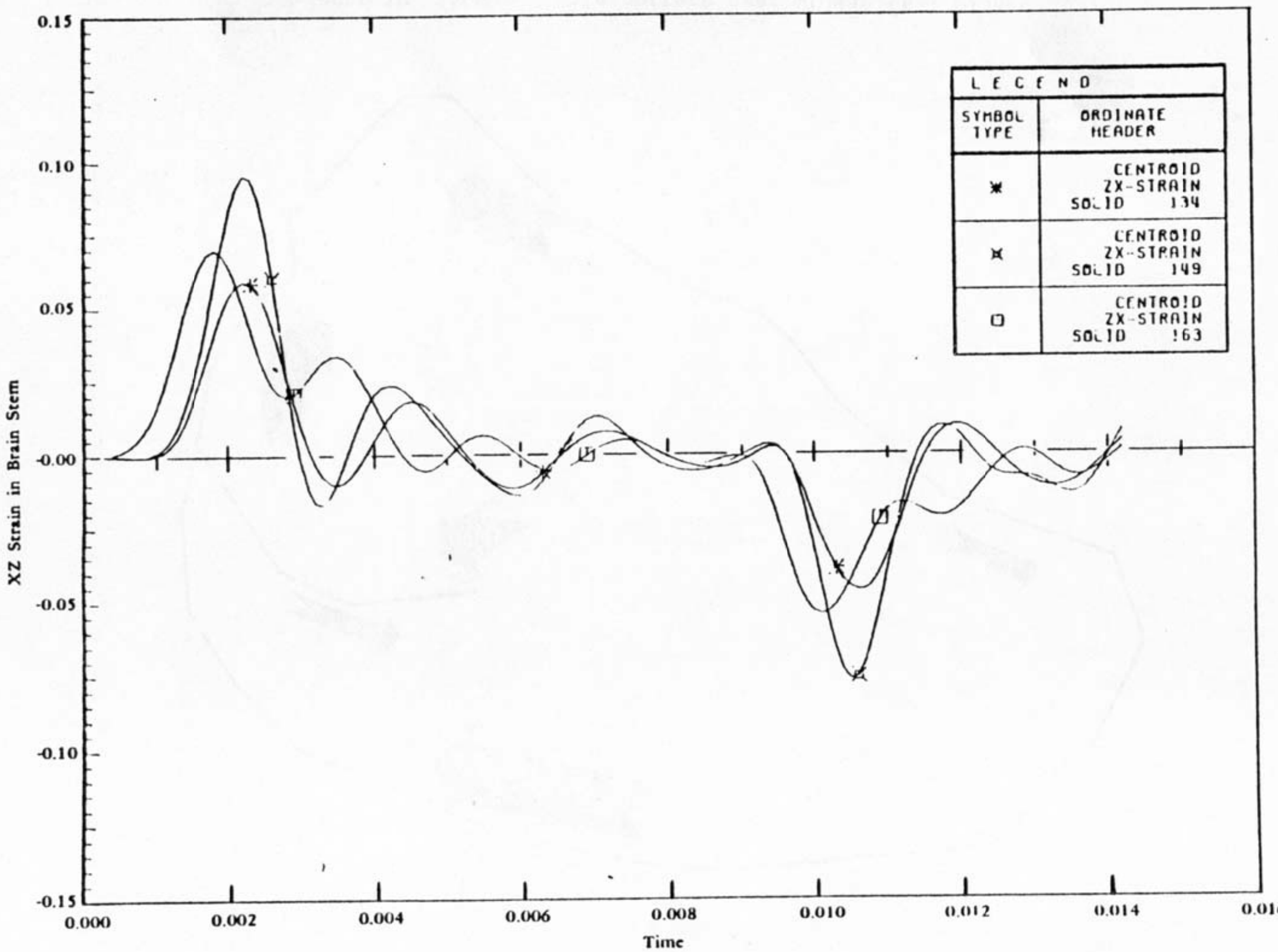

FIGURE 9. X-Z shear strains in vertical column of elements extending from the tentorium to foramen magnum

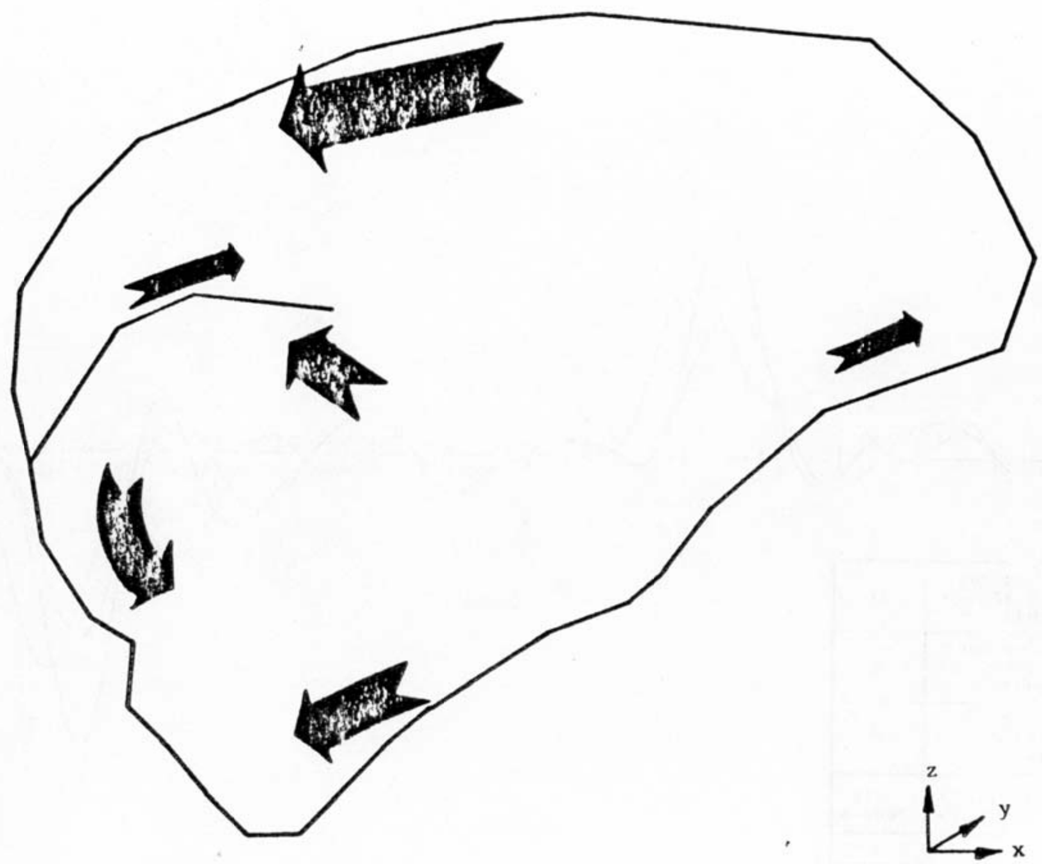

FIGURE 10. Shear strain pattern near midsagittal plane

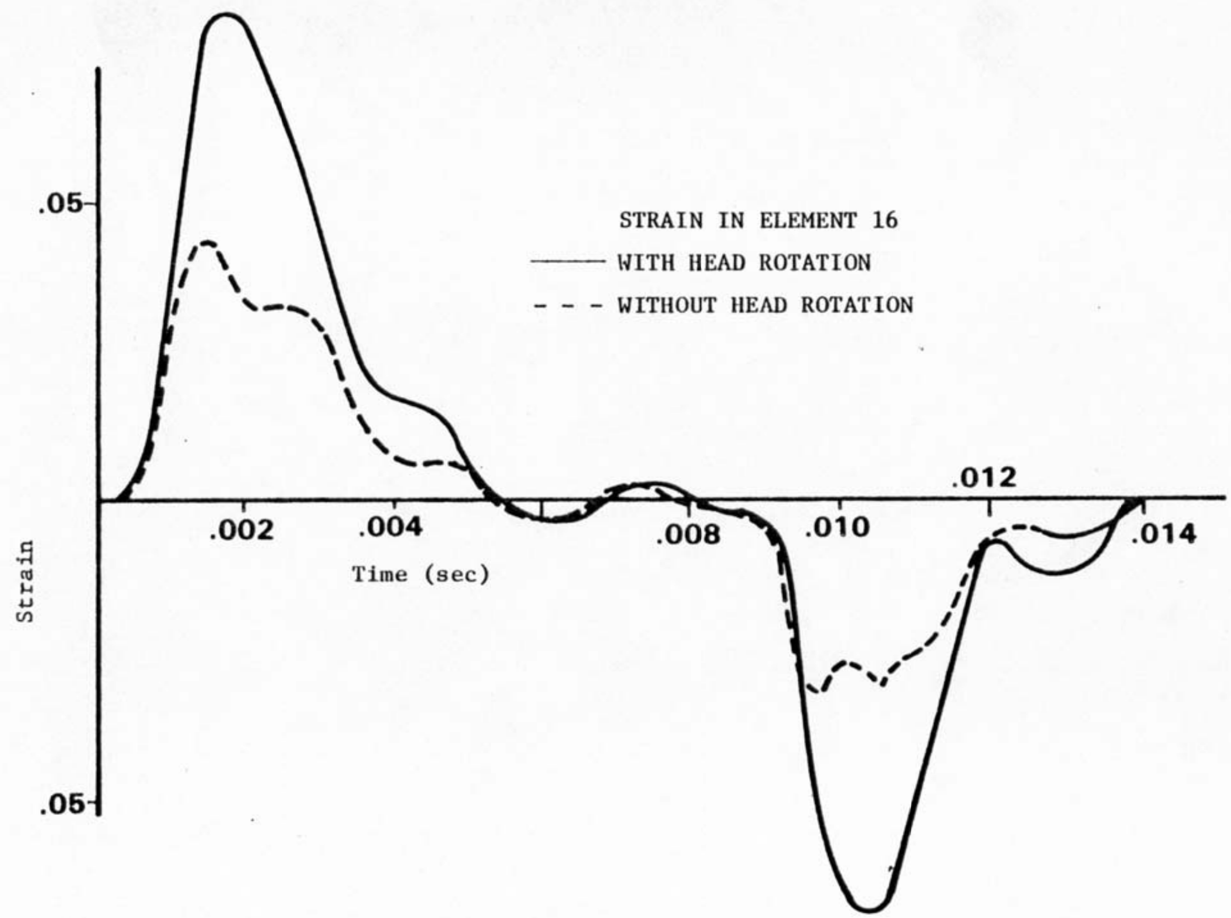

FIGURE 11. Comparison of cortex shear strain with and without head rotation